PL-TR-94-2191

GROUND TRUTHING TECHNOLOGIES FOR MINING AND NUCLEAR EXPLOSIONS

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June 1994

Final Report
July 1993 - June 1994

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PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
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SPONSORED BY
Advanced Research Projects Agency (DoD)
Nuclear Monitoring Research Office
ARPA ORDER NO 128

MONITORED BY
Phillips Laboratory
CONTRACT NO. F19628-93-K-0016

This technical report has been reviewed and is approved for publication.

JAMES F. LEWKOWICZ
Contract Manager
Earth Sciences Division

JAMES F. LEWKOWICZ, Director
Earth Sciences Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1994	Final (July 1993 - June 1994)

4. TITLE AND SUBTITLE
Ground Truthing Technologies for Mining and Nuclear Explosions

5. FUNDING NUMBERS
F19628-93-K0016
PE62301E
PR NM93
TAGM WU A A

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Southern Methodist University
Dallas, TX 75275

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Phillips Laboratory
29 Randolph Road
Hanscom AFB, MA 01730-3010

Contract Manager: James Lewkowicz/ GPEH

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
PL-TR-94-2191

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Seismic monitoring of a Comprehensive Test Ban Treaty may require the detection, location and identification of seismic events as small as mb=2.5 in limited areas. Considering the emphasis placed by the current Administration on such an agreement, it is important to assess the complexity of the proposed task. The discrimination between earthquakes, chemical mining explosions and nuclear explosions using regional seismic waves has been shown to be strongly region dependent. The establishment of a physical framework for discriminants is important if successful techniques developed in one region are to reliably transported and used in another location. Quick acquisition of region specific data, such as information related to crust and upper mantle velocity model, wave propagation characteristics and mining practices of interest, is required for practical implementation of a monitoring system. An experiment was executed during the last two weeks of August 1994 to test the applicability of such a seismic monitoring system combining near-source and regional data. It was conducted in and around an ore mine in Southern Russia. Validation of mining and blasting practices through direct field observations is identified as "ground truthing". These direct observations are compared to official records of blasting practices.

14. SUBJECT TERMS
Seismic Monitoring
Ground Truthing

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

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A COMPREHENSIVE TEST BAN TREATY

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THE ROLE OF PORTABLE INSTRUMENTATION IN MONITORING A COMPREHENSIVE TEST BAN TREATY

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Seismic monitoring of a Comprehensive Test Ban Treaty (CTBT) may require the detection, location and identification of seismic events as small as $m_b = 2.5$ (Wallace *et al.*, 1992) in limited areas of interest. With the emphasis placed on such an agreement by the current Administration, it is important to assess the complexity of the proposed task. The smallest events that must be discriminated from nuclear explosions include those associated with human activities such as construction and mining. These small magnitude events may be recorded by only a few regional stations (OTA Report, 1988). The lowest magnitude level to which monitoring must be accomplished is dependent on the quantification of various evasion scenarios, the most important of which may be decoupling (Murphy *et al.*, 1993; Stevens *et al.*, 1991).

To quantify the size of the monitoring problems, one must first relate the explosive yield of mining explosions to a magnitude measure. Israelson and Carter (1991) compare total explosive weight in ripple-fired explosions to M_L and suggest that in Fennoscandia a 25-50 ton explosion would have a M_L of 2.5 with a coupling scatter as great as a factor of 6-8. The magnitude-yield curves reported by Stevens *et al.* (1991) for unsaturated and saturated geologic materials at NTS predict m_b's for a contained 25 ton nuclear explosion of 2.04 to 2.64. Reamer and Stump (1991) compared near-source and regional measurements of a series of surface chemical explosions in the Western US. The 150 ton explosion in the series, assigned a M_L of 3.1 in the *Preliminary Determination of Epicenters* by the USGS, is consistent with these other results. These observations and models suggest that a monitoring threshold of 25-50 tons for ripple-fired explosions would be consistent with a

magnitude threshold near 2.5. The number of man made events greater than 50 tons in the US is 10,000 (Richards *et al.*, 1992) with one shot per day over 200 tons.

The discrimination between earthquakes, chemical mining explosions and nuclear explosions using regional seismic waves ($P/S/L_g$ ratios, spectral scalloping, frequency content) has been shown to be strongly region dependent (Patton, 1993; Baumgardt and Der, 1993). The establishment of a physical framework for discriminants is important if successful techniques developed in one region are to be reliably transported and used in another location. Quick acquisition of region specific data, such as information related to crust and upper mantle velocity model, wave propagation characteristics and mining practices of interest, is required for practical implementation of a monitoring system. The utilization of portable instrumentation provides the opportunity to acquire such information in the direct vicinity of the source as well as at regional distances. Digital data acquisition systems developed under the PASSCAL program linked with GPS clocks provide the necessary equipment for integrated near-source and regional studies.

An experiment was executed during the last two weeks of August 1993 to test the applicability of such a seismic monitoring system combining near-source and regional data. It was conducted in and around an ore mine located in Southern Russia at Tyrnyauz in the Caucasus Mountains (Figures 1 and 2). The goals of the deployment were: (1) document blasting practices: (2) quantify the coupling of seismic energy at close-in distances; and (3) resolve regional propagation path effects. The experimental work involved contributions from three institutions in Russia: *Experimental Methodological Expedition (Obninsk), Institute for Dynamics of the Geospheres (Moscow), Institute of Physics of the Earth (Moscow);* and two institutions in the United States: *Southern Methodist University (Dallas, TX)* and *Center for Seismic Studies (Arlington, VA).* Multiple types of observations were made of the explosions and included near-source and regional seismic ground motions, high speed film and video, electromagnetic measurements and field documentation. These data provided additional constraints to the seismic source and were used to interpret the adequacy of discriminants often applied only to regional seismograms. The focus of this note will be on the seismic observations, the field documentation and the video records from the explosions.

Validation of mining and blasting practices through direct field observations is identified as 'ground truthing.' These direct observations are compared to official records of blasting practices maintained by the mine. The types of information labeled as blasting practices include the size and types of boreholes, amount and type of explosive, and method and timing of detonation.

TYRNYAUZ MINE AND MINING PRACTICES

The Tyrnyauz mine is located in the Kabardino-Balkaria Republic of Russia close to the Georgian border (Figure 2). This particular mine was chosen for study because of a history of large explosions, two high-quality regional arrays, the occurrence of near-by earthquakes and cooperation with the mine operators. The city of Tyrnyauz has a population of 10,000 with half of these people employed in either the mining or the processing activities. Mineral exploitation began in 1940 in both underground and near-surface (cover photo) mines between 2400 and 3000 m. In the underground operation, over 150 km of 5.5 m diameter tunnels have been excavated. Both tungsten and molybdenum are extracted from the various metamorphic rocks present in this part of the Caucasus. The purpose of the blasting is to fragment the rock to sizes of 900 mm or less. These rock fragments are further reduced in size to 100-350 mm when they are dropped down a 700 m deep well for processing at lower elevations in the mine.

Typically both near-surface and underground production shots are detonated on Sunday mornings. The smaller underground explosions are completed first and consist of one to several charges detonated simultaneously. A near-surface explosion can involve many separate borehole explosions in rows on multiple benches or at different elevations. The individual shots within each row are detonated simultaneously with 20 to 40 ms delays between rows depending on the borehole depths. Boreholes are partially filled with a granular explosive consisting of 71% ANFO covered with an aluminum powder. The detonation is initiated with an electronic blasting machine which in turn ignites detonating cord with a burn rate of 7000 m/s. The purpose of the explosives is to fragment the rock with little or no concern for mass movement. As a result of this philosophy, the blasts tend to bulk the material moving it primarily in the vertical direction. Engineering records at the mine for 11 August 1991 to 28 August 1993 indicate that 6 surface explosions had yields in excess of 50 tons with an average explosion size of 33 tons for this time period. Underground and near-surface explosions were observed on 22 and 29 August 1993. On both days the underground explosions were detonated first with the near-surface following approximately one hour later. The sizes of these explosions were relatively small: 18.9 and 5.8 tons for the underground explosions and 25.3 and 7.3 tons for the surface explosions. The underground explosions consisted of one (29 Aug) and four (22 Aug) individual charges detonated simultaneously.

Official design records for the near-surface blasts were obtained from the mine engineers. Comparison between these records and the actual field deployment of explosives as well as video and photographic documentation of the near-surface explosion revealed wide discrepancies between the documented and actual explosions. Figure 3 compares the planned near-surface blast for 22 August according to official mine records (blue and green symbols) with that detonated as determined by field documentation (blue and white symbols). The total number of boreholes in the actual blast was reduced from that planned as well as the amount of explosive per hole. In addition, thirty bags of explosive (white spheres in Figure 3) were added to the near-surface explosion by draping them across large surface rocks. These bags (42 kg of explosive each) were not placed in boreholes and were intended to fracture large boulders remaining from previous blasts. The time between the rows of boreholes was increased from a planned delay of 25 ms to 40 ms. These changes resulted in a reduction in total explosive charge from 43.3 tons in the official records to an actual yield of 25.3 tons. A significant air blast was introduced from the bags of explosives placed on the boulders and the lack of stemming in each emplacement hole. The discrepancy between official mine records and actual blasting practice illustrates the importance of near-source monitoring of mining practices in order to fully assess source effects on regional seismograms. This 'ground truthing' provides the quantitative information that can be used to separate source and propagation path effects unambiguously at regional distances. Reliance upon official mining records may be misleading if this experience is typical of other mines. The changes that were introduced were brought about by the availability of explosive resources on the day of the shot and the local site geology as interpreted by the blaster. It is not unreasonable to expect similar variations in other mining operations.

Another aspect of the field documentation was the utilization of video and high speed film to determine the timing and regularity of the explosions. Figure 4 displays four video frames (sampled at 16.67 ms/frame) of the near-surface explosion on 22 August. As indicated in Figure 3, this blast occurred on two levels or benches. The first frame illustrates blasts on the first bench. The boreholes are not back-filled to the surface so that explosive by-products can be readily identified in the images. The second frame captures the detonation of bags of explosives on the first bench. These explosions are indicated by the bright orange images. The third frame illustrates the initiation of the first row on the second bench although all the boreholes do not fire simultaneously, probably as a result of

variations in the individual blasting caps in each hole. A number of authors have suggested that regular delay times between individual charges or rows of charges in this case may lead to consistent spectral scalloping in the Fourier spectra of the seismograms (Hedlin, Minster and Orcutt, 1989). These photos indicate that there may be variation between the design and actual shot times thus randomizing the spectral characterization and possibly degrading this discriminant.

SEISMIC INSTRUMENTATION

Near-instantaneous monitoring of man-made seismic sources requires a set of rugged and easily deployed instruments with relatively wide dynamic range. In addition, the data recovered from such a system must be combined in a timely manner with existing permanent regional seismic networks. These experimental goals led to the assembly of a portable instrumentation system for the near-source observations based upon two, six-channel Refraction Technology data acquisition systems (DAS), model 72-06. In order to span the range of ground motions expected in the near-source region, two sets of sensors were deployed with each DAS and included a three-component set of Terra Technology accelerometers and three-component Sprengnether S-6000 2 Hz seismometers. Timing and location information for each instrument was provided by a GPS receiver, making the near-source data available for immediate integration with the regional data. Sixteen-bit data were recovered at 500 samples/s in order to characterize the near-source ground motions. This data provided a wide-band picture of the source that could be compared to the other near-source observations such as the high speed photography.

Regional seismic data were recorded by Experimental Methodological Expedition (EME) operated facilities: two regional telemetry networks (RSS, installed by EME and a Nanometrics telemetry system installed by Lamont); the Kislovodsk micro-array (installed by CSS); and the broadband IRIS/IDA seismic station (installed by UCSD) (Figure 1). The RSS network includes 7 stations equipped with CM3-KB three-component seismometers and a data acquisition and recording system (designed by EME) with a sampling rate of 128 samples/s. The system has flat velocity response between 0.4 and 20 Hz. The Lamont system consists of seismometers collocated with RSS instruments and characterized by a flat velocity response between 0.2 and 24 Hz with a sample rate of 60 samples/s. The Kislovodsk 4-element micro-array with an aperture of 300 m is equipped with Teledyne-Geotech GS-13 seismometers -- three-components at the middle point and vertical only at the periphery. The instrument response is flat in velocity from 0.5 to 10 Hz and the data are sampled at 40 samples/s. The IRIS/IDA seismic station has three-component STS-1 seismometers with a flat velocity response between 0.003 and 5 Hz and is sampled at 20 samples/s.

NEAR-SOURCE DATA

The near-source data provide the opportunity to evaluate time and frequency domain differences between the simultaneous underground explosions and the ripple-fired near-surface explosions. Figure 5 compares the 22 August vertical velocity records from the near-surface and underground explosions at one of the near-source stations (S2). A number of source characteristics are immediately evident. First, the increased low frequency content of the near-surface explosion signal relative to the underground can be observed in both the time and frequency domain. The near-surface explosion spectrum is larger by as much as an order of magnitude in the frequency band of 1 to 5 Hz. The spectra from the two explosions merge at the higher frequencies although there is still considerable variation between the two at a given frequency. The total duration of the surface explosion is close to 200 ms and would predict a spectral hole at 5 Hz from this temporal window and suggests that source duration controls the spectral character in the 1

to 5 Hz band. Spectral interference from the interaction of the waveforms generated by each row is harder to identify in the spectra and may reflect the scatter in the individual detonations as identified in the video records. As noted in the explosion discussion, a significant variation from US blasting practices was the inclusion of free surface explosions in the mining blast and the lack of stemming in the emplacement holes. The high-frequency, late-time arrival on the vertical component of the near-source data is evidence of this air blast. Monitoring of such arrivals may be useful in identifying similar types of blasting practices.

REGIONAL DATA

The regional observations from the same explosions allow one to directly assess the effect of propagation path on the source signatures identified in the near-source data. Comparisons between the underground and near-surface explosions on 22 August are made at the regional stations KNG (28 km), KIV (65 km) and GUM (67 km) in Figure 6. The time series from the surface explosion at each of these regional stations are enriched in low frequency energy relative to the seismograms from the underground explosion. Inspection of the whole record spectra accompanying each waveform illustrates that the surface explosion is again enriched to about 5 Hz where the spectra from the two events merge. This comparison confirms that the increased energy from the near-surface blasts, identified in the near-source observations, is also reflected in the regional waveforms. These data suggest that bandwidth measures of regional signals may be used to separate different types of above and underground explosions. Such a discriminant would rely on relative wide band data, out to 10 Hz or beyond in this example.

The repeatability of the source excitation is important if pattern recognition is to be used to separate source types at regional distances. Comparison of the regional signals at three stations (GUM, KIV, KNG) from the underground explosions on 22 and 29 August (Figure 7) illustrates the strong similarity in bandwidth and arrivals from these two sources. Despite the known yield differences (18.9 and 5.8 tons) these records suggest that pattern recognition procedures as proposed by Rivière-Barbier and Grant (1993) might be successful in identifying events of a similar geometry. The differences identified in the near-surface and underground shot (Figure 5 and 6) argues that subtle changes in source depth and spatial or temporal characterization might also be identified with comparable techniques.

Regional arrival time data were used to locate the two explosions on 22 August in order to investigate location bias introduced by utilization of a regional 1D velocity model. The regional locations of the explosions are within 1 km of those determined by the field investigation (Figure 2). This comparison emphasizes the value of selected near-source observations for regional network calibration.

CONCLUSIONS/IMPLICATIONS

The detection, location and identification of small seismic events will increase in importance if a Comprehensive Test Ban Treaty is implemented. This experiment has illustrated the utility of combined near-source and regional observations in studying unusual or unidentified events. Digital data acquisition systems in combination with a GPS provide the means for a rapid deployment of portable instrumentation that can quickly be integrated with an existing permanent array. The availability of Internet services further provides for rapid access to the data following the experiment. Correlation and distribution of both the regional and near-source data were performed from KIV the day of the explosions. Anomalous events identified by regional signals under a CTBT can be investigated with a system such as that deployed at Tyrnyauz. The near-source observations in combination

with field documentation will provide additional data for improved event identification as a construction or mining activity. Studies such as this one can be used to identify important physical processes in the source region (total source duration and source depth in this case) that contribute to regional observations. The experiment has also identified significant variations between documented and actual blasting practices and suggests that care should be applied when using formal blasting records from a mining operation in the interpretation of regional seismic records.

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REFERENCES

Baumgardt, D. R. and Z. Der, Investigation of regional seismic discriminants using visualization and statistical analysis methods in the intelligent seismic event identification system, in the Proceedings of the 15th Annual PL/AFOSR/ARPA Seismic Research Symposium, 8-10 September 1993, Vail, Colorado, PL-TR-93-2160, ADA271458.

Hedlin, M. A. H., J. B. Minster and J. A. Orcutt, The time-frequency characteristics of quarry blasts and calibration explosions recorded in Kazakhstan, USSR, *Geophys. J. Int., 99,* 109-121, 1989.

Israelson, H. and J. Carter, Analysis of high frequency seismic data, PL-TR-91-2032, Phillips Laboratory, Hanscom AFB, MA, 1991, ADA235579.

Murphy, J. R., J. Stevens and N. Rimer, Theoretical simulation analysis of seismic signals from decoupled explosions in spherical and ellipsoidal cavities, **EOS, Transactions, American Geophysical Union, 74,** p 58, April 20, 1993.

Patton, H. J., Discrimination of low magnitudes: Summary of potential and recent results, **EOS, Transactions, American Geophysical Union, 74,** p 58, April 20, 1993.

Reamer, S. K. and B. W. Stump, Source parameter estimation for large, bermed, surface chemical explosions, *Bull. Seism. Soc. Am., 82,* 406-421, 1992.

Richards, P. G., D.A. Anderson, and D. W. Simpson, A survey of blasting activities in the United States, *Bull. Seism. Soc. Am., 82,* 1416-1433, 1992.

Rivière-Barbier, F. and L. Grant, Identification and location of closely spaced mining events, *Bull. Seism. Soc. Am., 83*, 1527-1546, 1993.

Stevens, J. L., J. R. Murphy and N. Rimer, Seismic source characteristics of cavity decoupled explosions in salt and tuff, *Bull. Seism. Soc. Am., 81,* 1272-1291, 1991.

U.S. Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties*, OTA-ISC-361 (Washington, DC: U.S. Government Printing Office, May 1988)

Wallace, T., R. Blandford, A. Dainty, R. Lacoss, R. Maxion, A. Ryall, B. Stump and C. Thurber, *Report on the DARPA Seismic Identification Workshop, 18-19 May 1992,* 28 pp.

Acknowledgments: Funding for this experiment was provided by ARPA under contracts F29601-92-C-005 (CSS), F29601-91-D-DB20 (SMU), F19628-93-K-0016 and by AFOSR under grant F49620-93-1-0146. Special thanks go to the EME staff at Kislovodsk for their field support, to the operators of the Tyrnyauz mine (particularly German Thedorovich Kazan), and to David Anderson at SMU for the image processing.

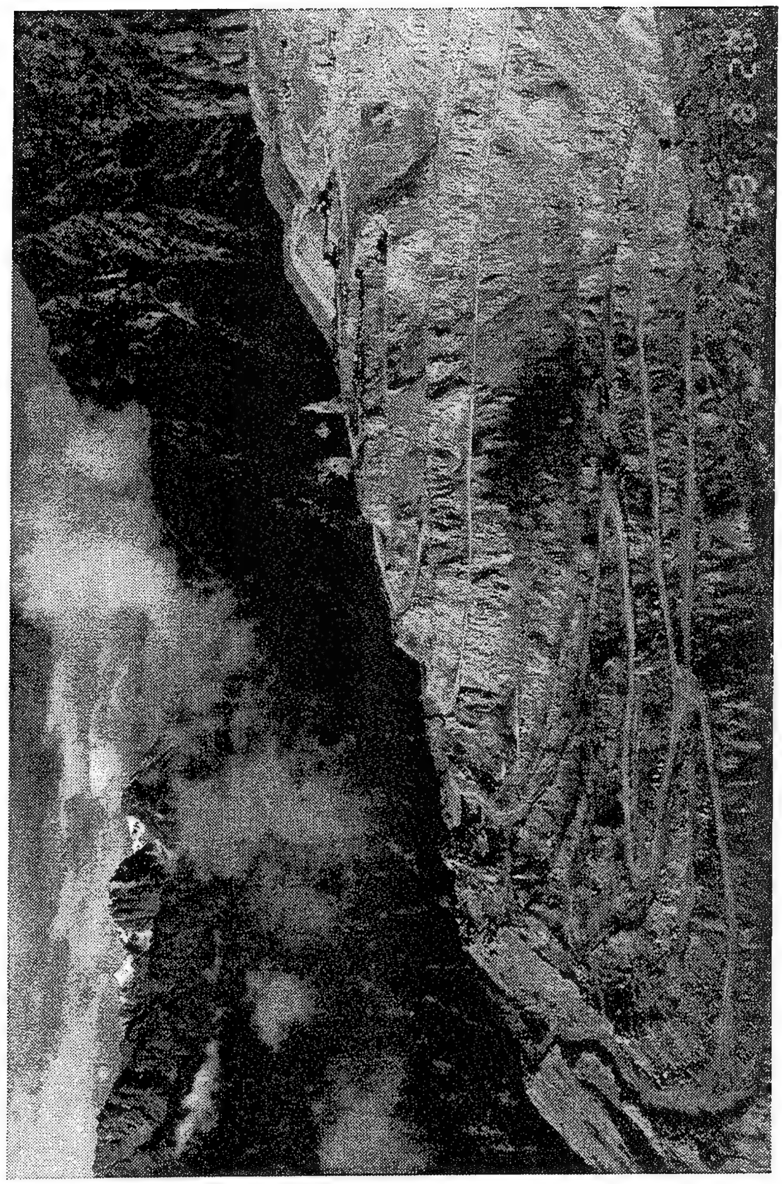
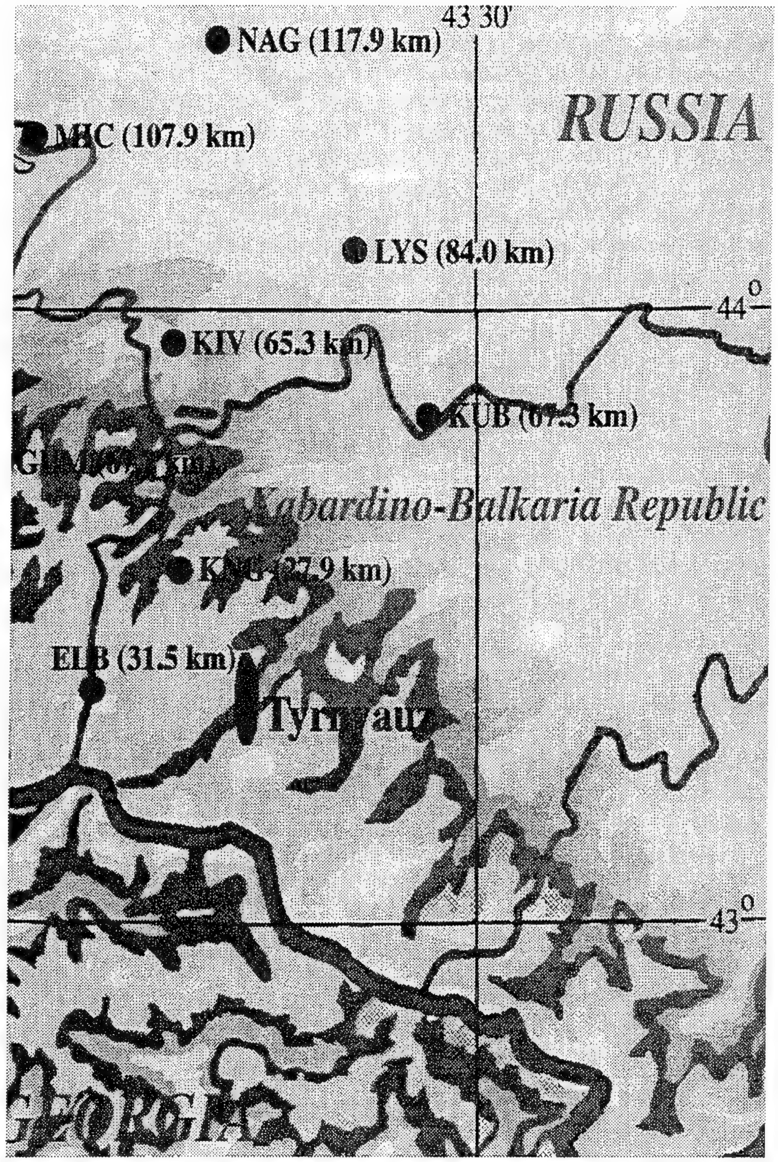


Figure 1



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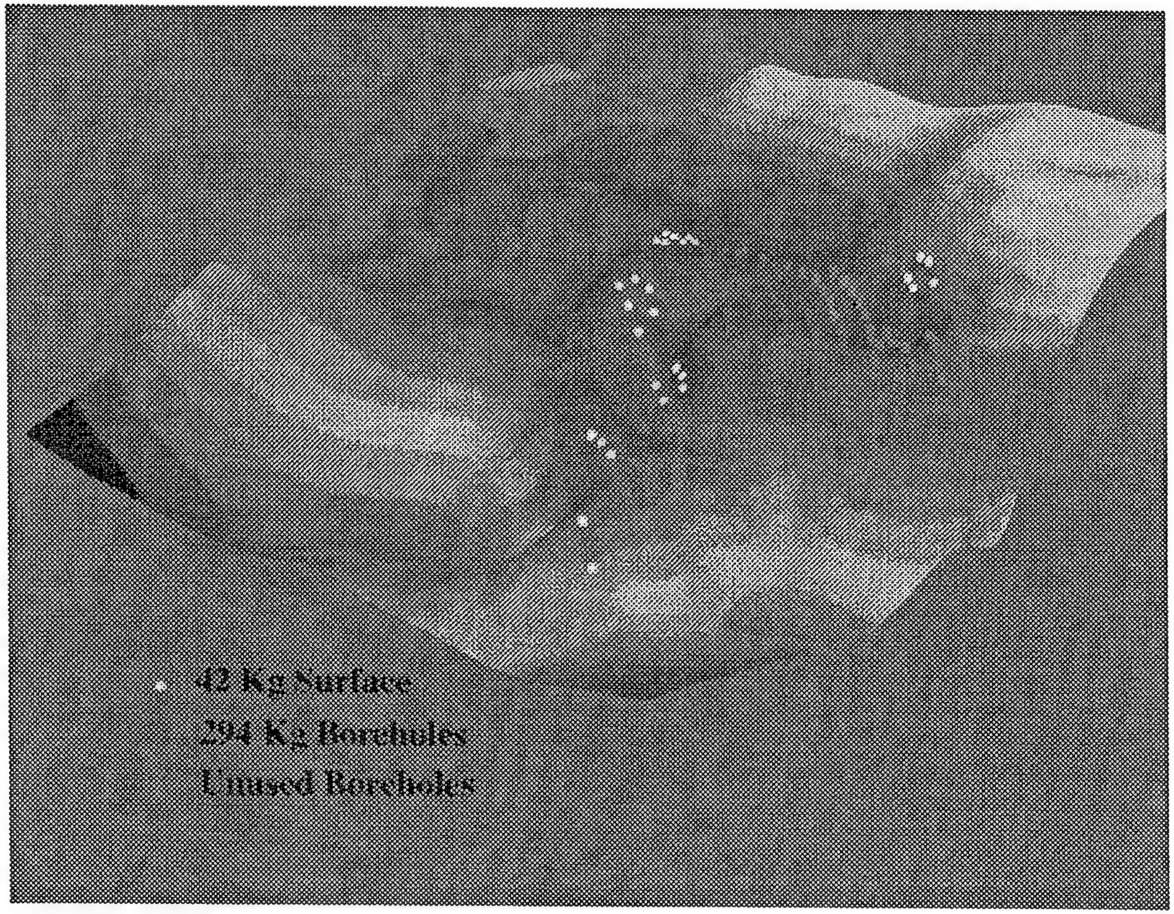
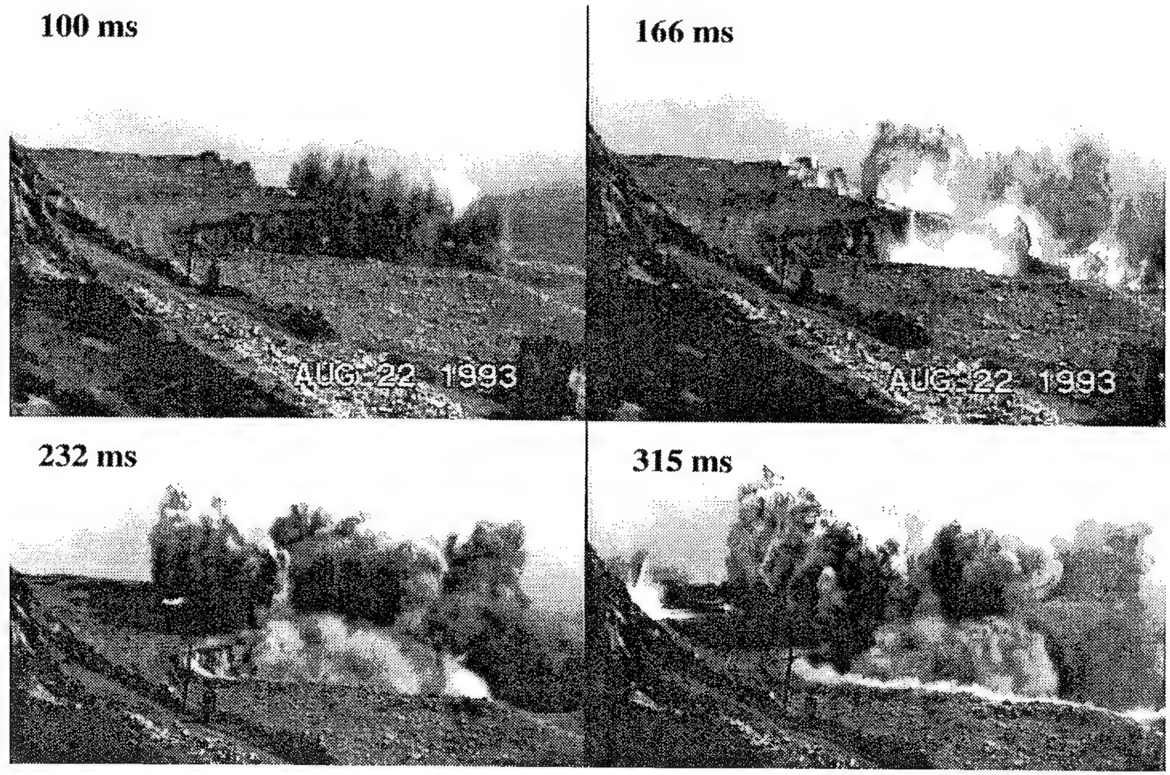


Figure 3



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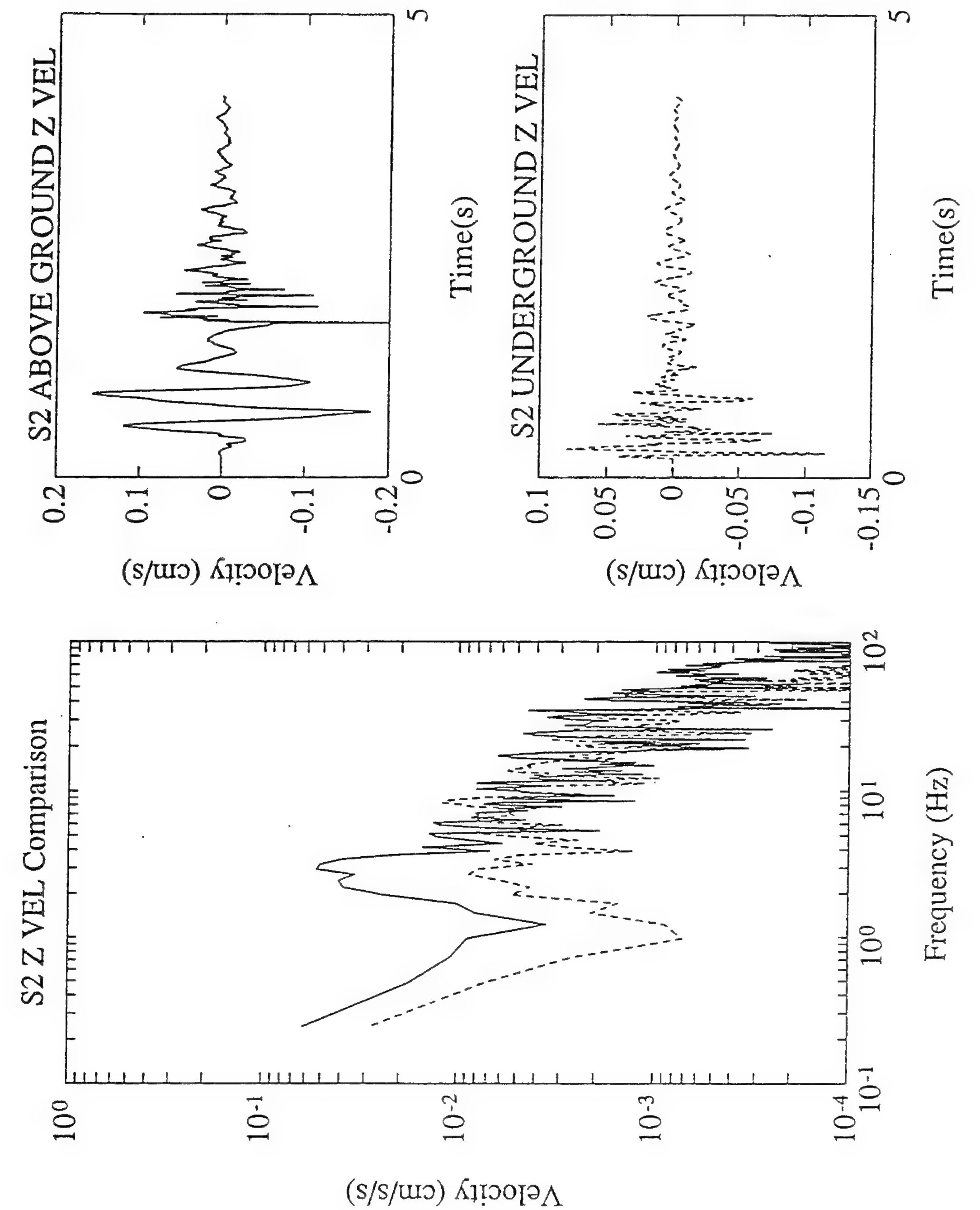
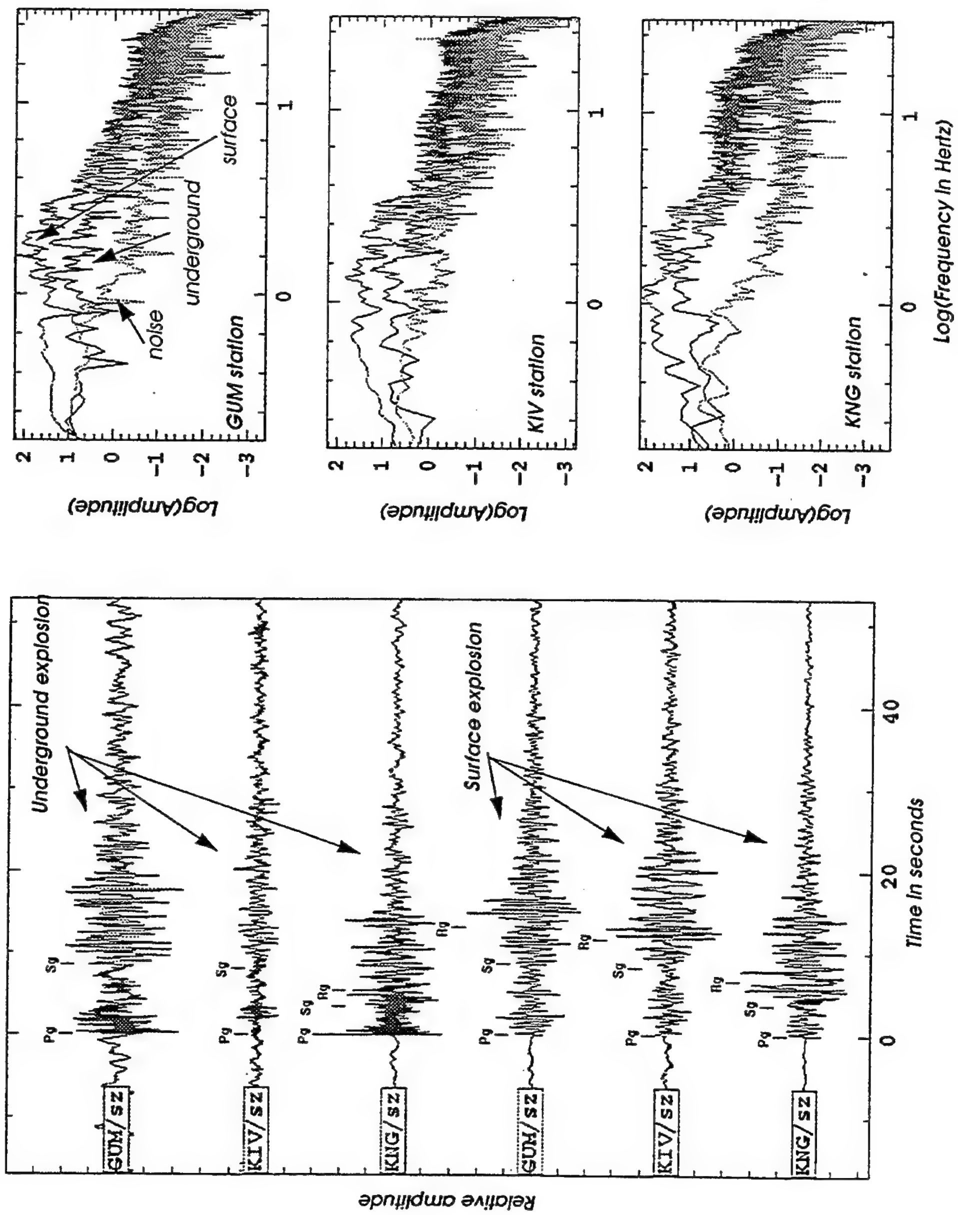


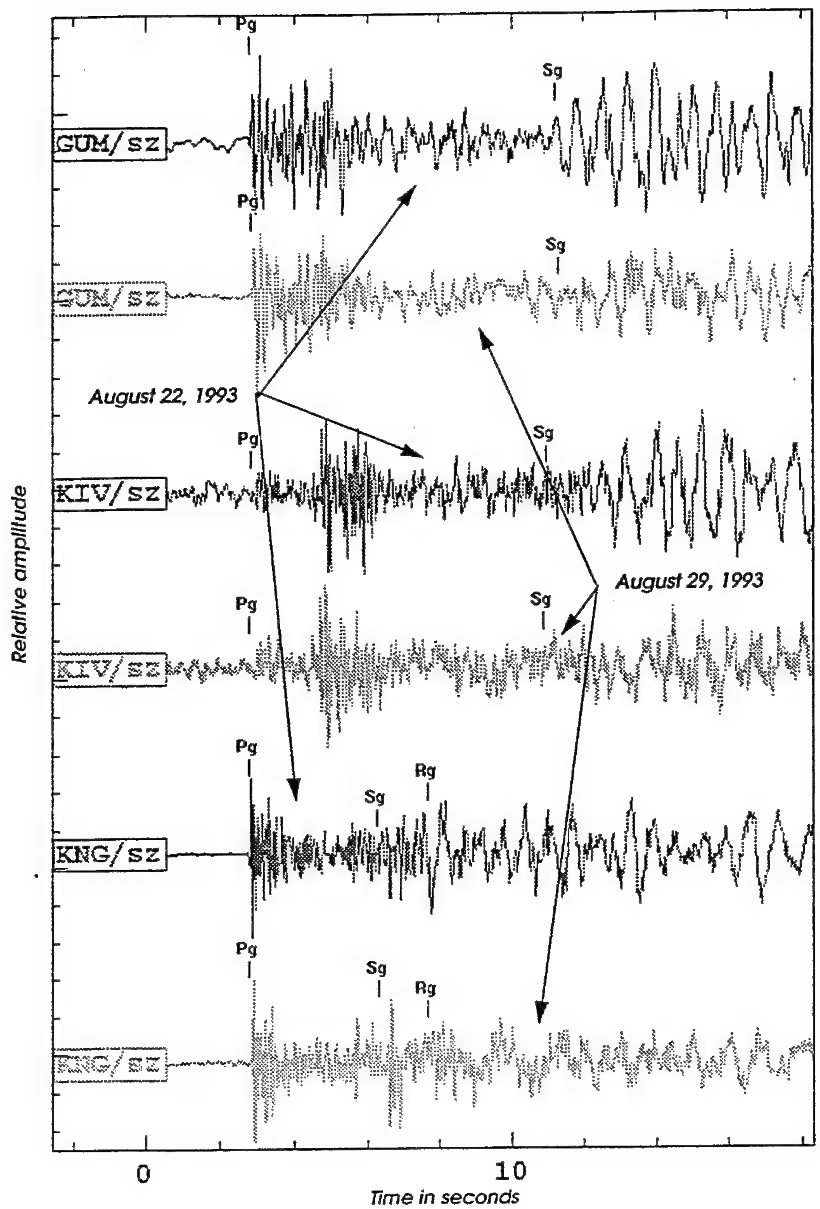
S2 Z VEL Comparison
Velocity (cm/s/s)
Frequency (Hz)
S2 ABOVE GROUND Z VEL
Velocity (cm/s)
Time(s)
S2 UNDERGROUND Z VEL
Velocity (cm/s)
Time(s)

Figure 5



Relative amplitude
GUM/SZ
KIV/SZ
KNG/SZ
GUM/SZ
KIV/SZ
KNG/SZ
Pg
Sg
Rg
Underground explosion
Surface explosion
Time in seconds
0
20
40
Log(Amplitude)
GUM station
KIV station
KNG station
noise
underground
surface
Log(Frequency in Hertz)

Figure 6



Pg
Sg
GUM/sz
Pg
Sg
GUM/sz
August 22, 1993
Pg
Sg
KIV/sz
Relative amplitude
August 29, 1993
Pg
Sg
KIV/sz
Pg
Rg
Sg
KNG/sz
Pg
Sg
Rg
KNG/sz
0
10
Time in seconds

Figure 7

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